

SCENARIOS OF HYPOTHETICAL WATER AND AIR INGRESS IN SMALL MODULAR HTGRs

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Abstract

The ingress of larger amounts of water, steam or air into the primary circuit of a high temperature reactor is seen to be an accident of considerable safety relevance. The overall destructive potential of these effects depends strongly on the quantities of the invading material as well as on the physical and operational boundary conditions of the reactor system at the time of the ingress. The safety analysis of water and air ingress accidents therefore is based on scenarios depending on the plant's conditions and considering different levels of protection systems failures. With respect to a catastrophe-free nuclear technology scenarios in the hypothetical area without any protection system action are of special interest. Starting from the knowledge on design basis accident behaviour of the German modular HTR this paper discusses some scenarios in the hypothetical accident field that should be analyzed in detail to find the limitations of the inherent safety features of this type of reactor. For some cases preliminary answers on the basis of less sophisticated computer models are given and suggestions for further developments and improvements of the reactor design are formulated.

1. Introduction

The ingress of larger amounts of water, steam or air into the primary circuit of a high temperature reactor is seen to be an accident of considerable safety relevance. The impact of these media to the graphite structures of core and fuel elements is twofold: By changing the concentration of moderating nuclei the neutron balance is affected and by chemical oxidation of the graphite the structural integrity of the core is attacked and explosive gases may be produced. The overall destructive potential of these effects depends strongly on the quantities of the invading material as well as on the physical and operational boundary conditions of the reactor system at the time of the ingress.

The safety analysis of water and air ingress accidents therefore is based on scenarios depending on the plant's conditions and considering different levels of protection systems failures. With respect to a catastrophe-free nuclear technology scenarios in the hypothetical area without any protection system action are of special interest.

Water ingress may be caused by ruptures inside the steamgenerator as a consequence of the much higher pressure in the secondary loop. The core can only be affected if larger amounts of steam or water will be transported from the steamgenerator to the reactor. The status of the primary blower plays an important role in this field and the condensation of steam on cold surfaces and within the gas volume is of major significance. The system pressure will increase and passive safety valves or burst-disks actions come into play. The neutronic reaction depends strongly on the fuel element design, i.e. moderation ratio of the core. In extreme scenarios positive reactivity feedback effects by temperature induced steam concentration reductions in the core after massive water ingress can be thought of. Finally a heavy corrosion of the fuel elements will change the geometry of the core and thereby influence the reactivity behaviour additionally. Of course these effects will depend on the effectiveness of the shutdown systems.

Air ingress is possible only after a depressurization accident has already taken place and has to be looked at as an accident with a very low probability. Nevertheless, scenarios of ruptures of pipes in the fuel handling system (pebble-bed) or in the shutdown system construction and other penetrations of the primary vessels (all designs) can be thought of. Without a self-sustained air massflow through the core, e.g. activated by the chimney effect, there is no larger damage to be expected. If ruptures of vessels like the large connection between reactor and steamgenerator are no longer excluded, air ingress scenarios of much larger safety relevance have to be analyzed. The corrosion of larger parts of the core at least for the pebble-bed design will change the core geometry and thereby the surface to volume ratio might be decreased with a significant impact on the decay heat transport to the environment.

Up to now impacts of water and air ingress have been analyzed in detail in the design basis area and in hypothetical situations assuming the integrity of at least part of the reactor protection systems. The results are encouraging showing the positive effects of the HTGR's self-stabilizing safety features. However, to ensure the final goal of a catastrophe-free nuclear energy technology, additional analyses of extreme hypothetical accident scenarios have to be performed and in parallel all activities in enhancing the passive corrosion protection of the graphitic fuel elements and structures should be enforced.

2. Water Ingress as a design basis accident

Within the scope of the Safety Report for the German MODUL-HTR as designed by the SIEMENS company [1] the water ingress is discussed with respect to reactivity effects

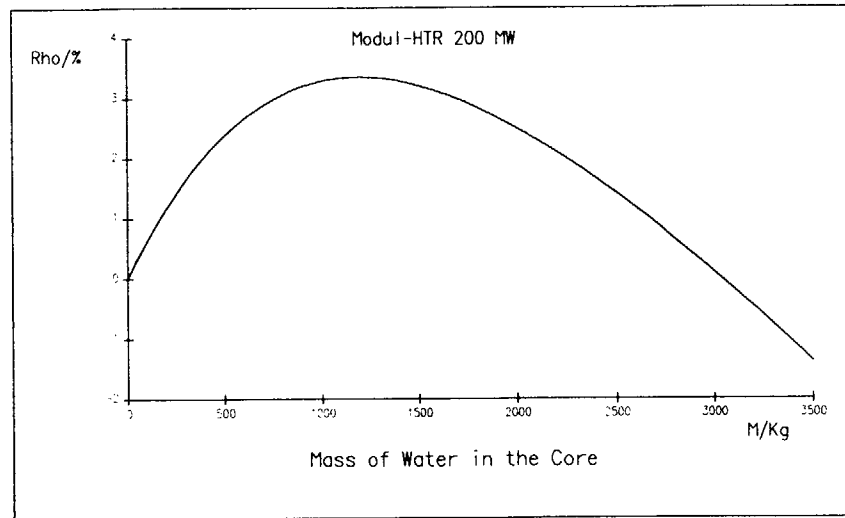


Fig. 1: Reactivity Effect of Water Ingress in the MODUL-HTR

and fuel element corrosion. The reactivity analysis is based on calculations assuming a homogeneous distribution of steam over the core. Static neutronics calculation then show that the reactivity introduced by the steam depends on the steam concentration as given in fig. 1. Because of the slightly undermoderation of the pebble bed core low steam concentrations increase the neutron multiplication as a consequence of better moderation. At a certain steam concentration depending on the fuel design and loading scheme a maximum reactivity is reached. Further increase of the concentration will decrease the reactivity as a consequence of the neutron absorption in the steam.

The figure shows that a maximum reactivity of about 3.5% is reached for a steam concentration that is equivalent to about 1000 kg water inside the reactor core. Assuming the break of one steamgenerator heating pipe and taking into account the activities of the reactor safety systems a maximum steam ingress rate of 5.3 kg/s and a maximum amount of less than 600 kg of steam/water was found for the primary circuit. As the core gas volume takes only a small part of the primary loop the maximum water ingress into the core itself was calculated to be less than 60 kg. This implies a reactivity effect of about 0.4% which is easily compensated by the control rods. Neutron dynamics effects were found to be much less severe than others already shown to be covered by the safety analysis. As 60 kg of steam will corrode no more than 40 kg of graphite the corrosive impact of this water ingress scenario is negligible.

Additional analyses of certain hypothetic scenarios [2] assuming partially failure of the reactor safety systems showed that even there no severe damage of the fuel elements will occur. From the point of view of today's licensing procedures which include the discussion of hypothetic accidents the design of the MODUL-HTR assures a maximum safety behaviour against water ingress from steamgenerator heating pipe rupture.

3. Hypothetic Massive Water Ingress with complete Failure of the Reactor Protection Systems

Within the scope of a catastrophe-free nuclear energy hypothetic events have to be analyzed to understand the general response of the nuclear system on such accidents and to determine the limitations necessary to prevent the environment from any damage.

With respect to water ingress the maximum amount of available water and the maximum pressure of the primary circuit that can be thought of define the ultimate limitations for this type of accident. Assuming that the water may enter the core but as steam either the safety valves and burst-discs or the failure of the reactor pressure vessel will define an upper limit for the water concentration in the reactor core. If the possibility of introducing liquid water (e.g. as droplets in the cooling gas) is not ruled out then even higher concentrations might be possible. The amount of water available is in the order of some hundred m³ (feedwater tanks). This is a very large quantity compared to what has been discussed in licensing talks. More over it is theoretically enough to have the potential to corrode the complete fuel element graphite. Keeping this in mind it becomes evident that the progress within a given time plays the main part in answering the question of whether this could be a really dangerous situation. To give at least some (in the moment naturally preliminary) answers some simple boundary conditions have been defined. To get a feeling for the differences in the dynamics of what has been discussed in the licensing talks and a extrem hypothetical event two scenarios are compared. Let us assume that we have a steamgenerator leakage by a broken pipe. This causes a water ingress at a rate of about 5 kg/s. The reactor safety system is assumed to fail partially, i.e. no shut-down rods will move in and the primary helium blower will continue to operate. If the total amount of water entering into the primary loop is limited to 600 kg, the basic response of the reactor will be as shown in the following figures.

Because of the positive reactivity of the ingressing steam (fig. 2) the reactor power will raise (fig. 3), which causes the temperatures to raise either (fig. 4) and thus compensate the excess reactivity. Because of the thermal inertia the induced reactivity is overcompensated (fig. 2). After 120 seconds the water ingress stops and so does the power excursion. As the nuclear power is still used to heat and evaporate the feedwater,

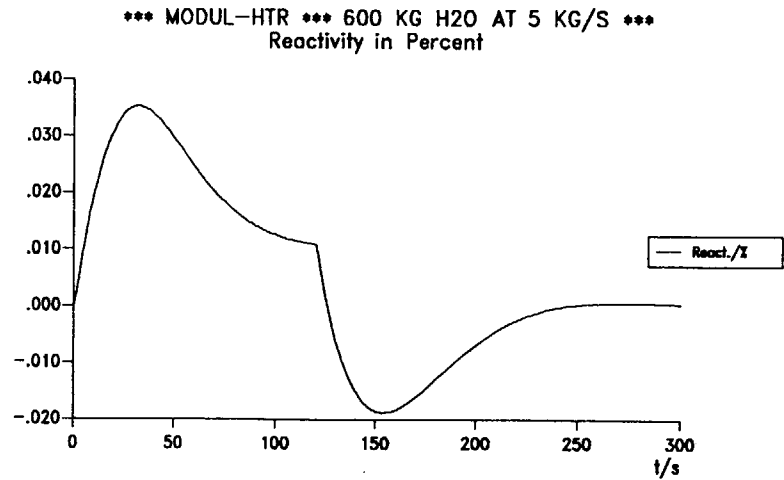


Fig. 2: Reactivity Transient for Ingress of 600 kg Steam into Primary Loop at a rate of 5 kg/s.

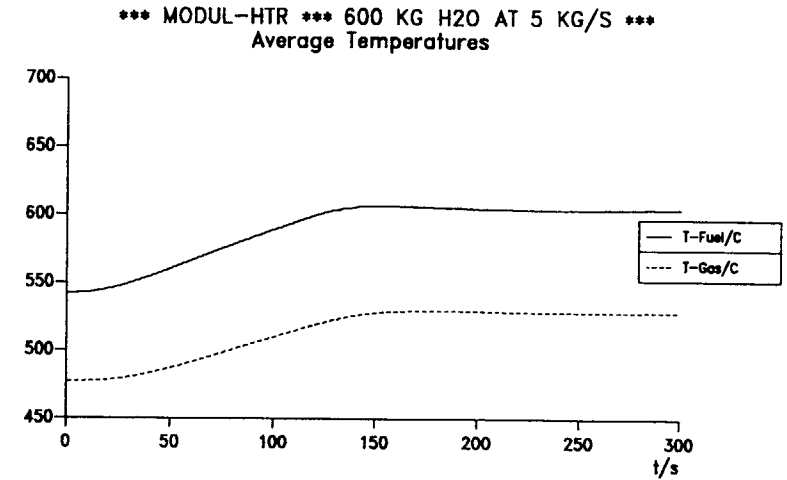


Fig. 4: Temperature Transient for Ingress of 600 kg Steam into Primary Loop at a rate of 5 kg/s.

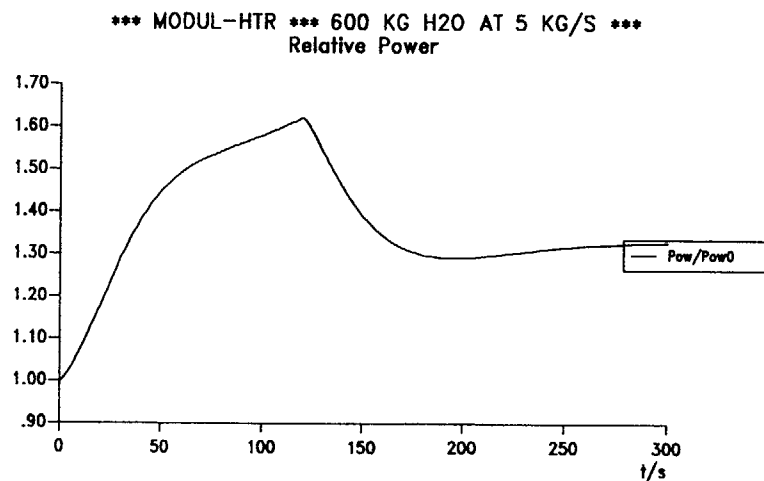


Fig. 3: Power Transient for Ingress of 600 kg Steam into Primary Loop at a rate of 5 kg/s.

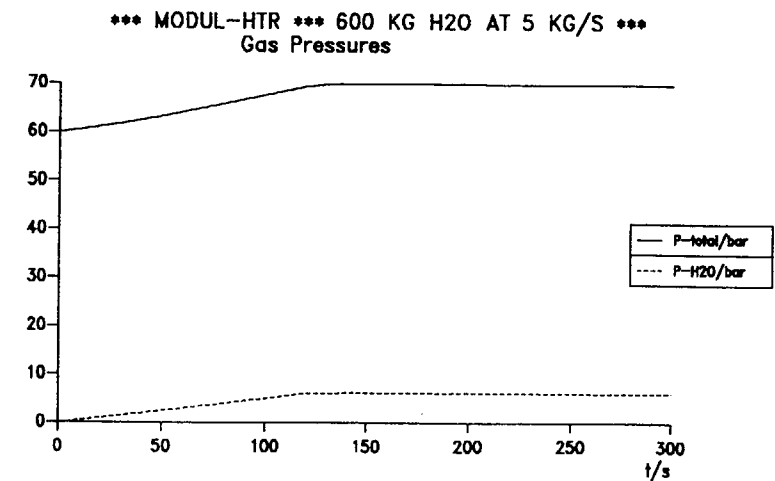


Fig. 5: Pressure Transient for Ingress of 600 kg Steam into Primary Loop at a rate of 5 kg/s.

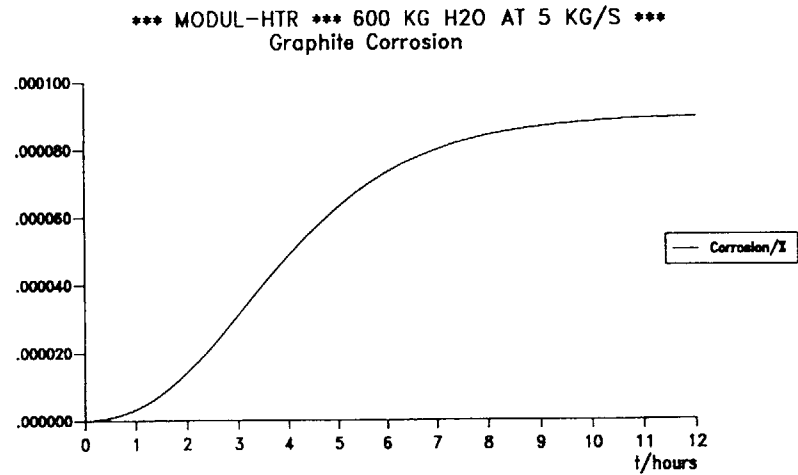


Fig. 6: Graphite Corrosion for Ingress of 600 kg Steam into Primary Loop at a rate of 5 kg/s.

there is no automatic shut-down of the reactor. After some time the pressure in the primary system reaches the safety valve action level (fig. 5). By opening of the valve the pressure will stay at that level and the helium cooling gas together with some of the steam is removed through the valve.

The nuclear dynamics is characterized by a power excursion with automatic power limitation and reduction due to the negative temperature feedback. The temperatures will raise in a very moderate way and so does the system pressure. There will be no short-time damage of the fuel elements. The average chemical corrosion is a very slow process (fig. 6) and there is a lot of time for accident management activities.

In the second example the complete reactor safety system is assumed to fail, i.e. additionally to the previous assumptions the feedwater pump will fail to stop, too.. A total mass of 90000 kg of water may enter the primary loop at a rate of 50 kg/s which is close to the nominal feedwater rate (77 kg/s) and may simulate a rupture of many steam pipes.

In this case after the safety valve has opened, by and by the complete helium in the system is exchanged by steam (fig. 10). If the safety valve and burst-discs are assumed to fail too, the increasing pressure finally will cause a massive failure of the pressure vessels which then is the limiting reason for further steam concentration increase.

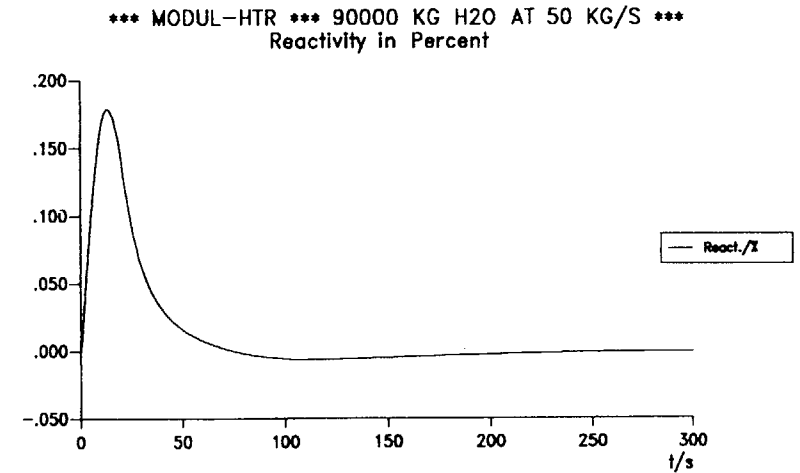


Fig. 7: Reactivity Transient for Ingress of 90000 kg Steam into Primary Loop at a rate of 50 kg/s.

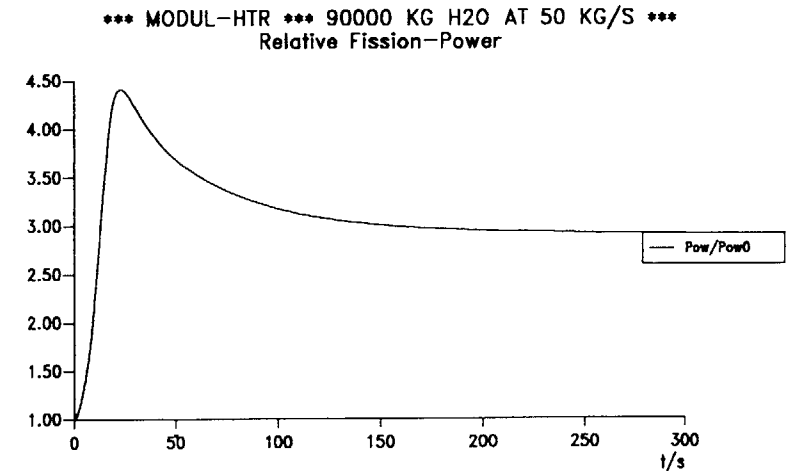


Fig. 8: Power Transient for Ingress of 90000 kg Steam into Primary Loop at a rate of 50 kg/s.

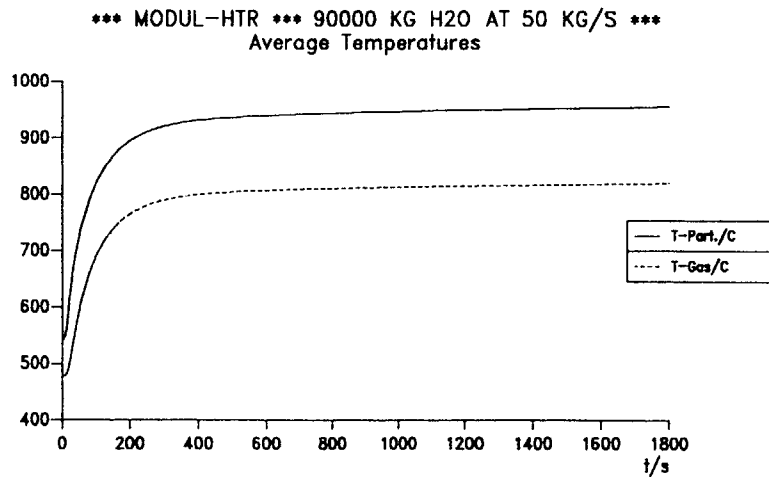


Fig. 9: Temperature Transient for Ingress of 90000 kg Steam into Primary Loop at a rate of 50 kg/s.

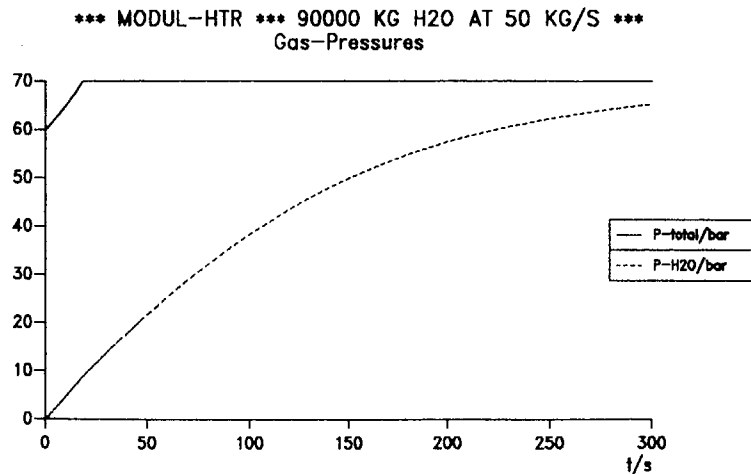


Fig. 10: Pressure Transient for Ingress of 90000 kg Steam into Primary Loop at a rate of 50 kg/s.

The reactivity (fig. 7) and nuclear power transients (fig. 8) now are much larger and faster. The maximum power reaches values of about five times the rated power and temperatures increase correspondingly faster (fig. 9).

Even in this scenario the short-time effects are not disastrous. The average graphite corrosion reaches values around 1% after many hours. However, the detailed corrosion distribution inside the core volume has still to be analyzed.

In both situations mentioned the reactor core stays at elevated temperatures. So the corrosion of the graphitic material keeps running until a temperature reduction becomes possible. This is the case (neglecting all activities of the safety system and by management) if about 20% of the core graphite has been corroded thereby reducing the graphite moderation of the neutrons and thus compensating the additional steam moderation. After this temperatures can decrease and the reactor power will automatically adjust to the heat removal rate from the reactor system.

The details of these scenarios ask for very elaborated modelling and computer codes. Especially the details of the corrosion process have already been investigated in the past by experimental activities [3,4] and are subject to extended computer modelling and code systems [5].

4. Hypothetic Air Ingress Scenarios

As already mentioned above the ingress of air into the primary loop of a modular HTGR is always an extremely hypothetic event with a very low probability. For such a situation to happen a complete loss of helium pressure must have preceded. Whether the consequences of air ingress are to be considered as severe or not depends strongly on the details of the scenario under discussion. For larger corrosion damage of the core and reflector graphite a continuous flow of air through the system with continuous removing of the reaction gases is necessary. This can be realized if position and size of a vessel leakage support a steady state natural convection (chimney effect) through the primary system. Detailed investigations in this field have been initiated [6] and principal results are already known from experimental work [7].

The natural convection flow moves upward through the core, passing first the bottom reflector and later on the active core. The oxygen of the incoming air therefore reacts mostly with the reflector graphite; the chemical reaction of the remaining oxygen reaching the core takes place within half a meter of core material [8] (fig. 12). In this region a strongly peaked corrosion of graphite is observed. Depending on the flow rate and duration of the air ingress for a pebble bed reactor the corrosion may reach the fuel

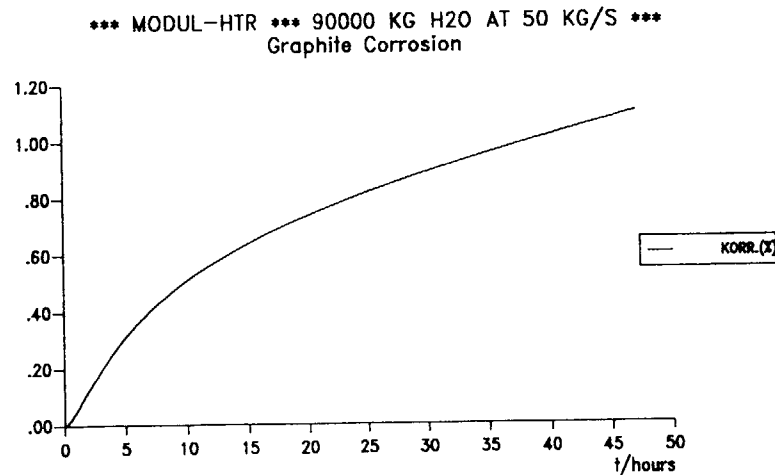


Fig. 11: Average Graphite Corrosion for Ingress of 90000 kg Steam into Primary Loop at a rate of 50 kg/s.

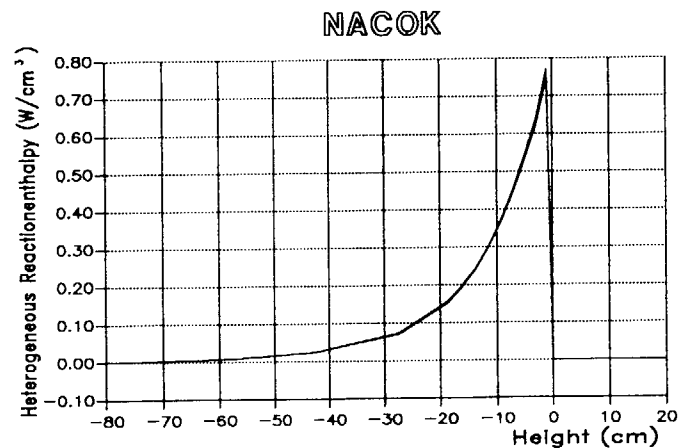


Fig. 12: Reaction Enthalpy for Heterogeneous Corrosion Reaction in the NACOK Experiment (Precalculation)

pellet and a movement of coated particles cannot be ruled out. The coated particles themselves however will not be attacked severely because of their SiC protection layer.

In this part of the core CO₂ is produced as reaction product. In the upper parts of the core this gas is partly reduced to CO thereby corroding additional graphite masses. However this reaction (Boudouard) is spread over a wide volume and so the additional corrosion per fuel element will remain small.

As examples for scenarios that could be thought of, the ruptures of pipes which are connected to the pressure vessels or even larger breaks in the vessels themselves should be mentioned [9].

For the case of anticipated ruptures in at least two connecting pipes (chimney effect) investigations show [10] the possibility of about 400 kg/day graphite corrosion. The relative homogeneous corrosion in the middle and upper core region is far less than 1 mm/day for pebble bed elements.

Assuming larger breaks in the pressure vessels for the pebble bed MODUL-HTR the rupture of the so called connecting vessel is of interest. Although in this case both ends of the 'chimney' are on the same height it was shown by theoretical and experimental analyses [11] that a natural convection is established that will lead to a corrosion of up to 1400 kg/day of graphite. In this case estimations show a corrosion of about 150-250 fuel pebbles per day in the most critical lower core region. The dynamics of a rupture of the Modul-HTR's connecting vessel will be subject to the NACOK experiment [6] now under construction in the Julich Research Center. The impact of such a scenario on the questions of coated particle movement through core and reflector and fission product release has to be analyzed in the future.

5. Conclusions

Water and air ingress into the primary loop of modular HTGRs lead to safety relevant consequences or larger damages only if extremely hypothetical scenarios are considered. These include the complete failure of the reactor safety and component protection systems and (for the water ingress) assume the operation of blowers and pumps under conditions far away from any design point. Even in such scenarios the reactivity increase induced by the additional moderation of the water does not lead to power or temperature excursions of major consequences. Optimizing the fuel element design the reactivity effect of ingressing water may be minimized or completely avoided [12]. However there are situations where the reactor does not automatically shut down although the power and temperatures are inherent limited. This is due to the further

operating heat sink. Supported by temperatures stabilized close to the design point the chemical attack to the graphite core and reflector structures stays for a long time and may cause major damage.

Concerning the hypothetical air ingress long term massive corrosion of a relative small number of fuel elements with liberation of coated particles cannot be ruled out at the today's level of knowledge. Although there are additional inherent mechanisms that will prevent larger amounts of radioactive products to leave the reactor (e.g. the adsorption of fission products in the colder graphite structures) technologies now in development to overcoat the fuel elements (esp. fuel pebbles) with a thin layer of SiC [13] will be able to diminish the corrosion rates by orders of magnitude and thus serve as the best design answer to overcome even the remaining hazard of the hypothetical scenarios as discussed here.

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